Precise Real-Time Low Earth Orbiter Navigation With GPS

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Biography

Willy Bertiger received his Ph.D. in Mathematics from the University of California, Berkeley, in 1976. In 1985, he began work at JPL as a Member of the Technical Staff in the Earth Orbiter Systems Group. His work at JPL has been focused on the use of GPS, including high precision orbit determination, positioning, geodesy, remote sensing, and wide area differential systems. He has been one of the chief designers and implementation experts of the core corrections for the FAA's WAAS and commercial WADGPS.

Bruce Haines his Ph.D. in Aerospace Engineering Sciences from the University of Colorado in 1991, after which he joined the Earth Orbiter Systems Group at JPL. He is a member of the Topex/Poseidon and Jason-1 Science Working Teams, and specializes in precise orbit and geodetic analyses using GPS and in oceanographic applications of satellite altimetry.

Da Kuang received his Ph.D. in Aerospace Engineering from the University of Texas at Austin in 1995. He joined JPL as a Member of Technical Staff in the Earth Orbiter System Group in 1996. Currently he is involved in work on Earth satellite orbit determination and navigational application of GPS.

Michael Lough obtained a Ph.D. in Applied Mathematics from the California Institute of Technology in 1995. Since 1997, he has worked in JPL's Earth Orbiter Systems Group, where he has focused on techniques for improving GPS-based precise orbit determination (POD) strategies for low-Earth orbiters.

Stephen M. Lichten received a B.A. from Harvard in 1978 and a Ph.D. from Caltech in 1983. He then joined the Jet Propulsion Laboratory (JPL) in 1983, initially working on very long baseline interferometry and precision GPS orbit determination. In 1996, he helped develop the Inter-Agency Agreement between NASA and the FAA which led to JPL's real-time GPS software development for the ground segment of the FAA's GPS Wide Area Augmentation System (WAAS), to be used for operational aircraft navigation in U.S. airspace starting in 1999. Steve also led a group which is responsible for the quick-look GPS-based precise orbits for Topex/Poseidon, current at the few-cm level of accuracy, which enabled the rapid dissemination of altimeter data, including widely publicized derived El Nino forecasts and advisories. He recently initiated efforts to develop innovative new radio metric tracking technologies, including the patent pending Autonomous Formation Flyer (AFF), which can provide precise autonomous navigation and formation flying for spacecraft ensembles. He is an inventor on 3 GPS-related patents recently submitted, and is currently the section manager for JPL's Tracking Systems and Applications Section.

Ronald Muellerschoen received a B.S. degree in physics at Rensselaer Polytechnic Institute and a M.S. degree in applied math at the University of Southern California. He is currently a Member of the Technical Staff in the Earth Orbiter Systems Group at the Jet Propulsion Laboratory (JPL). His work at JPL has concentrated on the development of efficient filtering/smoothing software for processing GPS data and delevopment of wide area differential systems.

Yvonne Vigue-Rodi received B.S. and M.S. degrees in Aerospace Engineering from the University of Texas at Austin in 1988 and 1990. She has worked as a Member of Technical Staff in the Earth Orbiter Systems Group at JPL, since 1990. Currently, she is involved in the development, implementation, testing and verification of high-precision automated GPS-based orbit determination software for Earth science applications.

Sien-Chong Wu is currently a Technical Group Leader in the Tracking Systems and Applications Section at JPL. He has been involved with the development of various tracking systems for deep-space as well as near-Earth space vehicles, and their applications to precision geodesy. His current interest is in the area of real-time wide-area differential GPS and special applications of GPS technologies. Sien received his Ph.D. from the University of Waterloo, Ontario, Canada.

Abstract

navigation

Technology is currently available to support real-time on-board knowledge of the position of a low earth orbiter at the 5-15 meter level using the civilian broadcast GPS signal with sophisticated models and filtering techniques onboard the spacecraft. Without these techniques, the standard positioning service yields 50-100 meters with the current level of SA. Proposed augmentations and/or enhancements to the GPS system will make RMS accuracies of 10 centimeters to a few decimeters available to the real-time on-board user.

Presently, near real-time processing of GPS tracking data can routinely provide low-Earth orbit determination accuracy at the level of 5 cm. Such processing systems can, in fact, be fully automated: recent results from the Jet Propulsion Laboratory (JPL), where ongoing daily processing of low-Earth GPS tracking data has been undertaken for several years, are presented in this paper showing orbit determination accuracies at the sub-10 cm level. At the present time, such solutions can be produced with about 10 hrs delay after real-time, but recent improvements in JPL's processing system will soon enable turn around at the 1-hr level or better for such precise orbit determination. We anticipate that orbit determination at the 1-cm accuracy level will be demonstrated, with some refinements to the current system, in the not too distant future.

Continuing enhancements in the automation of data retrieval and precise orbit processing will result in continuing decreases in latency for ground-based generation of precise orbit products for Earth orbiters. Such ephemerides can be propagated ahead slightly to provide real-time knowledge. However, there are advantages to an onboard, real-time orbit determination capability. These include unique mission requirements (military, strategic, scientific), as well as the potential to dramatically lower navigation operations costs through the enabling of a fully autonomous spacecraft. JPL has been actively involved in the development of technology to enable a fully autonomous spacecraft in low-Earth orbit. This paper includes recent results of analysis of actual and simulated GPS data collected in space which demonstrate that a 10-cm (or better) real-time onboard orbit determination capability is presently technologically feasible. In addition to space-based data, present-day tests in real time of Wide Area Differential GPS (WADGPS) on aircraft in real time, show upper bounds for space based users with a global WADGPS at the level of 30 cm RMS horizontal and 60 cm RMS vertical. The paper describes several alternative technology roadmaps which can be followed to make such a capability routinely available to a wide range of low-Earth orbiters. The discussion will include the use of Wide Area approaches as well as non-WADGPS approaches for achieving this capability. In addition to supporting a sub-10 cm real-time onboard positioning capability in Earth orbit, this system could also support a few decimeters real-time kinematic positioning for ground, sea, and air users globally.

Introduction

The Global Positioning System (GPS) is now used extensively for orbit determination by scientific and other Earth satellites, and for many other science, government and commercial purposes around the world. For users without selective availability (SA) keys, GPS currently provides real-time kinematic positioning (no use of dynamic orbital models) at the level of 50-100 meters. The majority of GPS users will be well served by the present system, or by widely available commercial differential GPS (DGPS) systems, which can provide meter to several-meter real-time accuracy over prescribed local regions. However, a subset of users will continue to seek something more, both in geographical coverage and in positioning accuracy.

Many of these stricter demands will come from science activities around the world, representing interests such as satellite remote sensing, aerogeophysics, and in situ Earth science on land and water. Prominent among prospective space-based users are the space shuttle and space station, which, because of high drag (and frequent maneuvering by the shuttle) tend to follow irregular orbits. A variety of shuttle- and station-borne instruments would benefit from real-time accuracies of a few meters or better.

For space missions requiring ultra-precise satellite orbit determination, such as the sub-10 cm accuracy demanded for satellite altimetry programs of the TOPEX/POSEIDON class [*Bertiger, et al.* 1994] a real-time, onboard orbit determination capability could enable computation of onboard geophysical data records in real- or near real-time. Such geophysical records could be transmitted to science investigators directly, greatly simplifying and reducing operations costs.

Several commercial space missions are imminent, which will utilize onboard GPS receivers for precise orbit determination (POD) in low-Earth orbit [*Los Angeles Times*, 1997] Those missions currently require extensive ground-based operations to retrieve and rapidly process the GPS flight and ground data for POD. The orbit information is then used after the fact at a mission processing center to calibrate remote sensing data. Near real-time or real-time POD would enable this information to be delivered immediately to time-critical users of the commercial systems. For instance, low-Earth orbiter imagers can track agricultural conditions and farm yields, measure vegetation coverage, help locate fish and game, survey habitats of endangered species, measure changing global climatic conditions, and survey chemical components of the Earth's surface. A global WADGPS, or an equivalent Enhanced GPS capability, would, if sufficiently accurate, enable extensive ground operations in these systems to be considerably reduced or even eliminated. When we use the words "Enhanced GPS," we refer to the several possible improvements in the GPS system itself which will probably include the removal of the SA clock dither and the addition of a second civil frequency. In addition measurements made between GPS spacecraft (cross links) may enable real-time corrections to GPS clocks.

Table 1. GPS Performance Requirements

Accuracy required, real-time	Technique	Users and Applications
100 m — 1000 m	SPS* GPS	Satellite routine navigation; low-cost terrestrial positioning
1 m — 20 m	WADGPS or PPS* GPS	Precise satellite navigation; surveying; aircraft (cruise) navigation; military uses
< 1 m	Precision WADGPS or Enhanced GPS (EGPS)	High precision satellite navigation; geodesy; high precision surveys; aircraft takeoff and landing navigation; SAR and precise Earth mapping

*SPS — Standard positioning service, available to civilian users without decryption. Note that current 50-100m positioning errors will improve to 10 m when selective availability is turned off.

*PPS — Precise positioning service, available only to users authorized to carry decryption

A tri-agency effort involving NASA, NOAA, and the U.S. Department of Defense (DoD) to develop a new generation of operational weather satellites is considering instruments that will require real-time position knowledge to a few decimeters. In addition, various proposed free-flying space missions, including microwave and laser altimeters, synthetic aperture radar (SAR) mappers, and multispectral imagers, are seeking orbit accuracies ranging from centimeters to one meter. While for many this performance is not needed in real time, the ability to achieve such accuracy autonomously onboard could save greatly in the cost of ground operations.

Many GPS science applications utilize terrestrial vehicles rather than Earth orbiters. Synthetic aperture radar (SAR) imaging, topographic mapping, gravimetry, and other forms of remote and in situ sensing are carried out with balloons, aircraft, ships, buoys, and other vehicles. One of the most stringent goals comes from airborne SAR investigators, who wish to control aircraft flight paths in real time to at least a meter, and eventually to a few centimeters. Comparable goals apply to real-time kinematic geodesy, which could be much simplified and readily extended to remote locations with global sub-decimeter positioning. A variety of mobile science instruments worldwide could generate finished products in real-time, ready for interpretation, with significant savings in data transmission and analysis costs. The scientific appeal of seamless worldwide positioning offering precise post-processing performance in real-time can hardly be overstated.

Table 1 lists some major categories of performance for real-time positioning with GPS. The paper focuses on two key areas of technology improvements to support high precision LEO positioning: 1) improved onboard models and filtering including dynamics and GPS measurement models; and 2) seamless global WADGPS or an Enhanced GPS. The combination of these two elements can yield sub-meter performance. At JPL, we have developed Real-Time Gipsy (RTG) as a general software package which implements item (1). Flight tests onboard a NASA DC-8 using a commercial WADGPS signal [*Bertiger, et al.* 1998; *Whitehead, et al.* 1998] will be presented showing RMS errors of 30 cm in the horizontal components and 60 cm in the vertical using codeless dual-frequency GPS data and corrections broadcast through a Geostationary satellite. Since the DC-8 is not in orbit, the software onboard the cannot take advantage of the precise dynamical models in the RTG software, but it does demonstrate a complete end-to-end real-time system in actual operating conditions. This same system will be flown as a navigation experiment on the X33 (experimental NASA/Lockheed reusable launch vehicle) using a single frequency GPS receiver. In addition to the real-time DC-8 flight experiments, we have processed stored GPS data from orbiting receivers as if it were real time, to demonstrate on-orbit performance with the current GPS constellation, a global WADGPS system, and possible enhancements to the GPS system itself.

Before presenting the results of our real-time experiments, we will show the current state of near real-time systems for low earth orbit with samples from JPL's current operational processing of Topex/Poseidon.

Topex/Poseidon Operational Near Real-Time and Predicted Orbits

Topex/Poseidon is a joint U.S. and French mission to measure ocean height [*Fu et al.*, 1994]. Onboard are three precise tracking systems: satellite laser ranging (SLR), Doppler orbitography and radio positioning integrated by satellite (DORIS), and GPS. DORIS is a French doppler system with excellent world-wide coverage. GPS was flown as an experiment onboard and was not the primary tracking system. When Anti-Spoofing (AS) is on, the GPS receiver onboard Topex/Poseidon operates as a single frequency receiver recording both phase and CA range for processing on the ground. At JPL, we have for several years produced operational GPS determined orbits [*Muellerschoen, et al.*, 1995; *Lough et al.*, 1998] of Topex/Poseidon with a typical latency of 11-17 hours after the last GPS data point was received onboard the spacecraft. Data from the spacecraft are transferred to JPL in 24 hour files. Together with the Topex/Poseidon altimeter data, the resulting orbit solutions are used to support a variety of operational oceanographic applications. Most prominent is the assimilation of near real-time sea-surface height data into the operational forecast model at the National Center for Environmental Prediction. The use of T/P altimeter data with the near real-time GPS-based orbits improved the model's forecast skill, and contributed to the early prediction (6-month lead time) of the 1997–1998 El Nino [*Cheney et al.*, 1998]. The definitive orbits (POE) used in the final science products are delivered by Goddard Space Flight Center to investigators with a latency of about 40 days and are generated using SLR and DORIS data. Since the spacecraft is using a radar altimeter to measure the distance between it and the ocean surface, the critical orbit component is the radial component (center of the earth to the spacecraft).

The definitive orbit(POE) currently has an accuracy of 2-3 cm in the radial component. Fig. 1, shows the JPL operational orbits over 10 days compared to the precise POE. The RMS difference over 10 days is 3.7 cm. The radar altimeter measurements can be used to infer a radial RMS accuracy of 2.4 cm assuming the POE orbit has a radial RMS accuracy of 2 cm. The JPL orbits are fully automated and require the efforts of less than one full-time person to produce.

The GPS operational orbits discussed above can be used to predict the orbit to real-time, making a high quality orbit

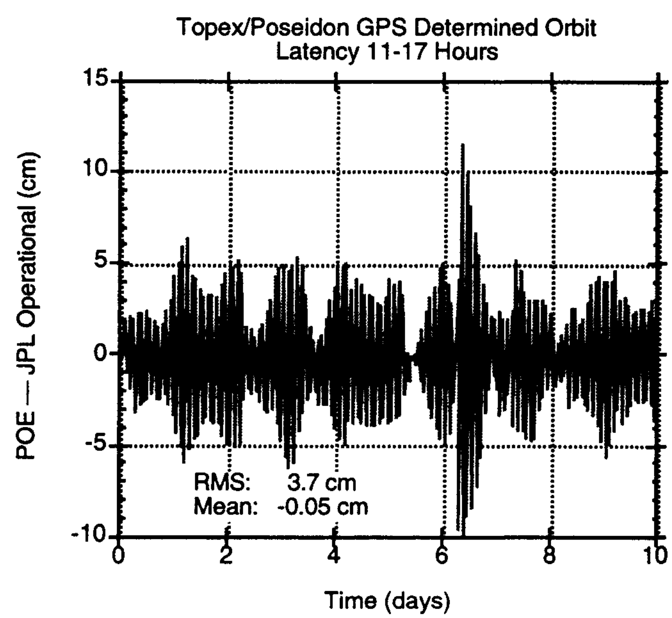

Fig. 1, JPL Topex/Poseidon Daily Operational Orbits compared to Definitive Precise Orbits. Operational Orbits are available 11-17 hours after the last data point.

available at the same time with the radar data. Table 2, shows the error in the orbit predicted 27 hours into the future over the same 10 day time period shown above. Typical RMS real-time radial accuracy is 5.6 cm using the predicted orbits.

Table 2, RMS errors in operational orbits predicted to real-time

day	Radial (cm)	Cross Track (cm)	Along Track (cm)
98apr28	2.7	3.9	16.7
98apr29	4.9	5.6	67.0
98apr30	7.3	3.9	34.9
98may01	5.3	8.5	161.6
98may02	6.0	7.6	40.9
98may03	2.5	12.3	63.4
98may04	10.0	8.5	126.9
98may05	8.4	6.1	146.4
98may06	5.6	6.8	106.1
98may07	3.1	4.7	30.1
Average RMS	**5.6**	**6.8**	**79.4**

To obtain these types of accuracies with a single frequency receiver in an operational mode, required extensive development of both the force and signal modeling. See *Lough et al.* [1998] for details.

Real-Time DC-8 Flight Experiment

In order to test Wide Area Differential Real-Time (WADGPS) positioning in an aircraft environment tests were conducted on a NASA DC-8 aircraft. The primary mission of the aircraft test flight was collection of synthetic aperture radar (SAR) measurements of the surface of the Earth. Real-time sub-meter positioning can significantly reduce SAR mission costs. The goal of the WADGPS experiment was to demonstrate absolute positioning in earth-fixed coordinates to better than 1 meter in all components. The tests showed real-time RMS accuracy in the vertical to be 60 cm with an RMS horizontal accuracy of better than 30 cm. Various tests of our post-process truth positioning methods indicate that the truth positioning is better than several cm RMS.

The real-time DC-8 solutions were produced using differential corrections transmitted through a Geostationary satellite to a receiver on-board the DC-8. Much of the software producing the corrections is licensed by SATLOC from JPL [*Whitehead, et al.* 1998 ; *Bertiger et al.* 1998]. This software referred, to as Real-Time Gipsy (RTG) and Wide Area Ionosphere (WIS), computes corrections to GPS orbits, clocks, and the ionosphere. This software system has also been licensed by Raytheon as the prototype for the FAA's Wide Area Augmentation System (WAAS) [*Ceva et. al.* 1997]. In addition to the receiver for differential corrections, there was a standard dual-frequency Ashtech Z12 for GPS data and a laptop computer for performing real-time positioning using RTG software [Bertiger et al. 1998]. Earlier flight tests used a single frequency Ashtech G12 receiver and identified several software improvements which were used in the flight reported on here. This flight also led to improvements and bug fixes which we believe will further improve the real-time performance. Further details of the system can be found in the references.

Figure 2 shows the two hour flight path of the DC-8 from Edwards A.F.B. to the Los Angeles region, and finally over the Pacific ocean. The crossing tracks over Los Angeles were flown to collect data for the primary mission, SAR, while the circles over the Pacific ocean were flown to support calibration of a cloud observation instrument. At that point, the laptop computer which was processing the real-time positioning with RTG failed.

The resulting two-hour real-time 1-Hertz solution was differenced with a truth solution generated by post-processing the raw GPS data from the same Ashtech Z12. The post-processing used a worldwide network of GPS receivers to determine the GPS orbits, and a network of 5

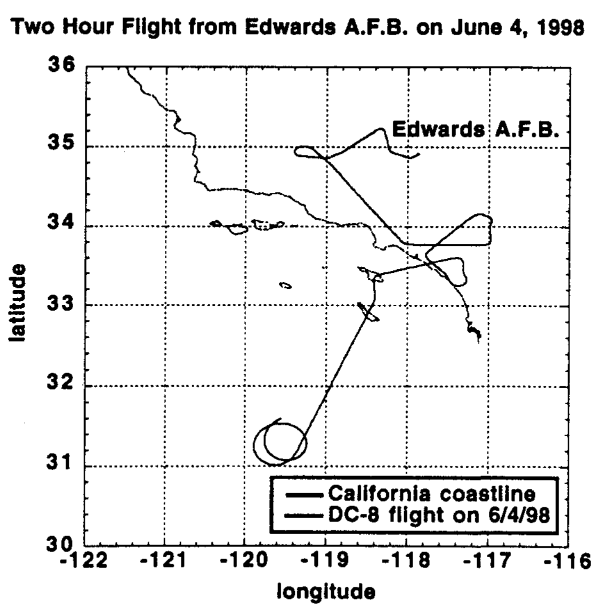

Fig. 2, DC-8 Flight, June 4, 1998

ground stations over the mid and western United States to generate 1 second GPS clocks. To validate the truth solution, the same post-processing data methods were used on a fixed receiver at a known location. Table 3 shows that this validation resulted in RMS errors at the 1 cm level.

Table 3, Truth Solution Test of a Stationary Receiver

	Mean (cm)	Standard Deviation (cm)	RMS. (cm)
East	0.2	0.6	0.6
North	-0.2	0.6	0.7
Vertical	0.5	1.5	1.6

Table 4 gives the accuracy statistics in East, North, and Vertical components for the phase center of the GPS antenna mounted on the upper portion of the DC-8 fuselage. The large means are probably due to errors in how the carrier phase bias breaks were determined. These processing errors have since been identified and corrected.

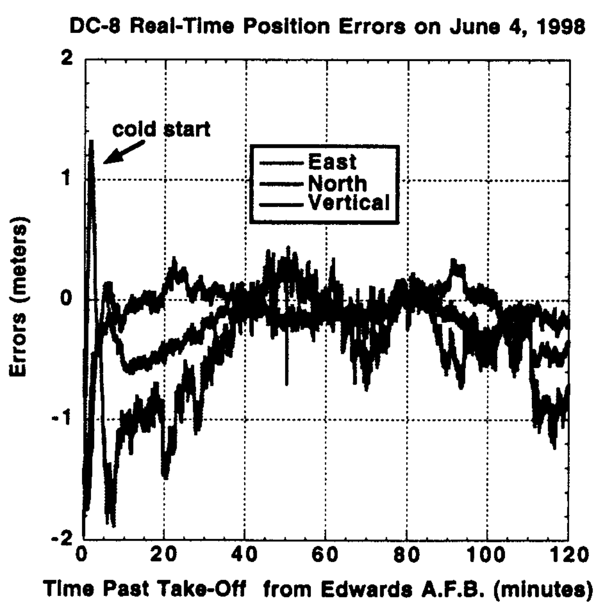

Fig. 3, DC-8 Real-Time Position Errors, June 4, 1998

Table 4, DC-8 Real-Time Position Errors, June 4, 1998

	Mean (cm)	Standard Deviation (cm)	RMS. (cm)
East	-16.5	21.9	27.5
North	-12.9	25.8	28.8
Vertical	-41.7	47.8	63.4

Fig. 3, shows a plot of the errors in time corresponding to the statistics shown in Table 4.. The larger errors at cold start are due to the initial poor determination of the GPS carrier phase biases.

Topex/Poseidon Real-Time Orbits

To test the performance of GPS in real-time on a low earth orbiter (LEO), actual GPS data from Topex/Poseidon were processed on the ground as it would be onboard, with software such as RTG. Since the data were processed from files rather than a data stream, Gipsy/Oasis II (GOA II) [*Wu, et al.* 1990, *Webb et al.,* 1993] was used instead of RTG for convenience. Almost all the precise models in GOA II are identical in RTG and would be available in

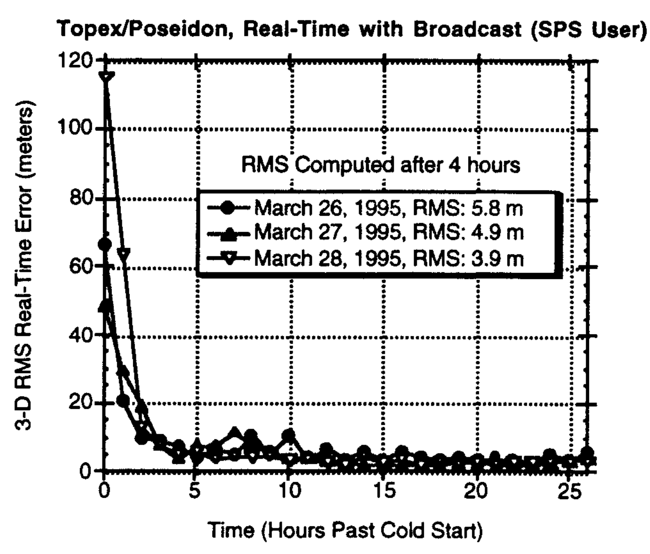

Fig. 4, 3-D Error after a cold start using Broadcast GPS Orbits and Clocks for Topex/Poseidon at 1300 km altitude

flight code. Compiler options allow optimization of load size for flight applications of RTG in embedded processors.

Fig. 4, shows the results with 3 days of data from 1995. Each line represents a cold start with the 3-D error plotted every hour for 27 hours. The dynamical models smooth out the effects of SA after about 4 hours. RMS error after the 4 hour convergence period is 3-5 meters. SA errors dominate and are at the typical level of 25 meters RMS.

Global WADGPS, Enhanced GPS

The orbit accuracy shown in Fig. 4 is realizable today using existing software (RTG for instance) and existing flight hardware (RAD 6000 for instance). Increases in a accuracy will be obtainable in the future through various proposed global enhancements to GPS. These enhancements may include improvements to the GPS infrastructure and technology, or enhancements to the WADGPS augmentation systems, or both. Examples of the latter include implementations of WAAS-like systems in various countries around the world [*Ceva*, 1997] — that is, the establishment, effectively, of global WADGPS capability. The U.S. government sponsored WAAS implementations are making plans for data interchange which would make global seamless corrections to GPS available. Enhancements to the GPS system include better broadcast orbits and clocks, turning off SA, second civil frequency, and real-time clock synchronization via satellite cross links. Below we use Topex/Poseidon and a lower orbit spacecraft at 700 km, GPS/Met [*Muellerschoen, et al.*, 1995; *Bertiger and Wu*, 1996], to illustrate the expected performance of onboard, real-time orbit determination, with some of the upcoming changes to GPS. All of the cases make use of actual data taken onboard the spacecraft, but here we simulate a range of expected improvements to the GPS system from global WADGPS or enhanced GPS. Two cases were considered to bracket the expected errors of possible global or enhanced GPS systems: 1) Use the broadcast orbit as the real-time GPS orbit. Fixing this orbit, use data from 20 global ground stations to solve (filtering only no smoothing) for the GPS clocks. 2) Use the precise orbit (good to about 20 cm) as the fixed GPS orbit and add white noise at each measurement time to the GPS clock determined with the precise orbit. Case 1) will be pessimistic with respect to the orbit error. Case 2) might be optimistic compared to some global systems, but may be a reasonable representation of possible future capabilities. Case 1) will be referred to as broadcast orbits with enhanced real-time clocks. Case 2) will be referred to as precise orbits and clocks.

Broadcast Orbits, Enhanced Real-Time Clocks, Case 1)

Onboard data from Feb. 20, 1997 (different from the above tests), for Topex/Poseidon were filtered as if processed in real-time. The broadcast orbits on this day, happened to be atypically bad, so the broadcast GPS orbits were adjusted to more typical errors shown in Fig. 5. This adjustment was made by scaling the difference in the broadcast GPS

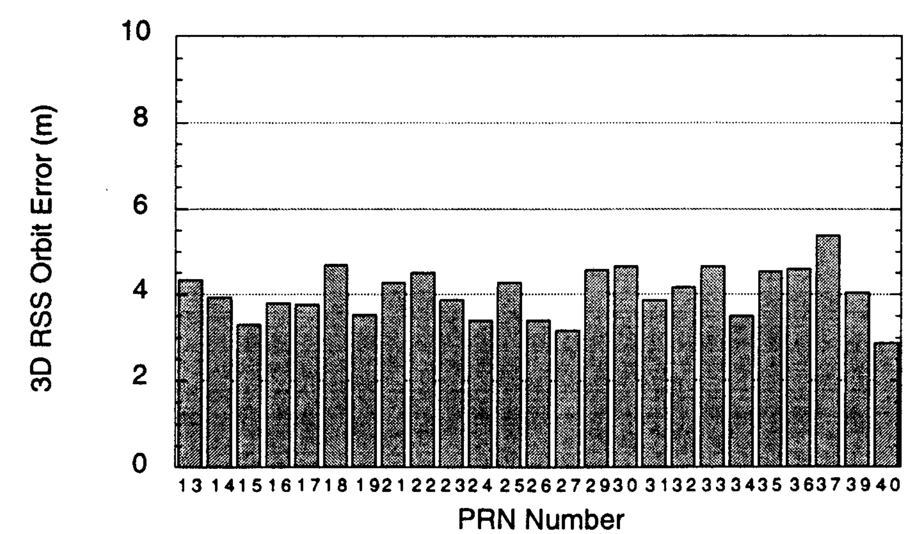

Fig. 5. Adjusted broadcast GPS orbit errors used in Topex/Poseidon data demo

orbits and the precise GPS orbits determined after the fact

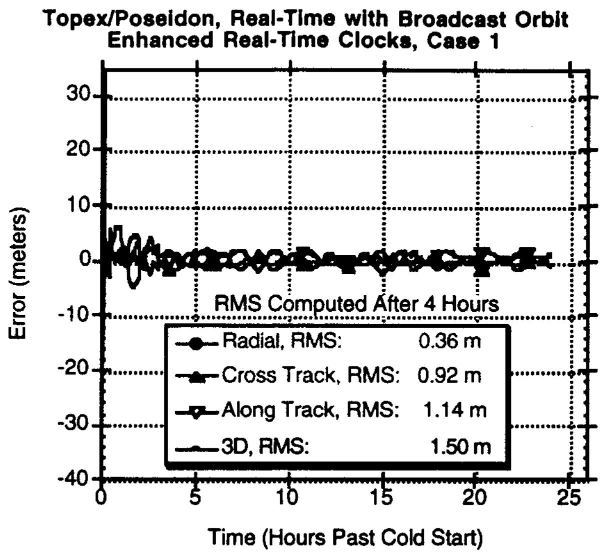

Fig. 6. Topex/Poseidon real-time position accuracy with broadcast level GPS orbits error and enhanced real-time clock errors

(good to about 20 cm). We will now refer to this adjusted orbit as the broadcast orbit. Fig. 6 shows the results of this solution. The enhanced clocks lead to much more rapid convergence of the solution following cold start than the above case with broadcast orbits and broadcast clocks. RMS radial accuracy is less than 50 cm with errors in the other components of about 1 m.

Fig. 7, shows a similar scenario for GPS/Met. It carries a

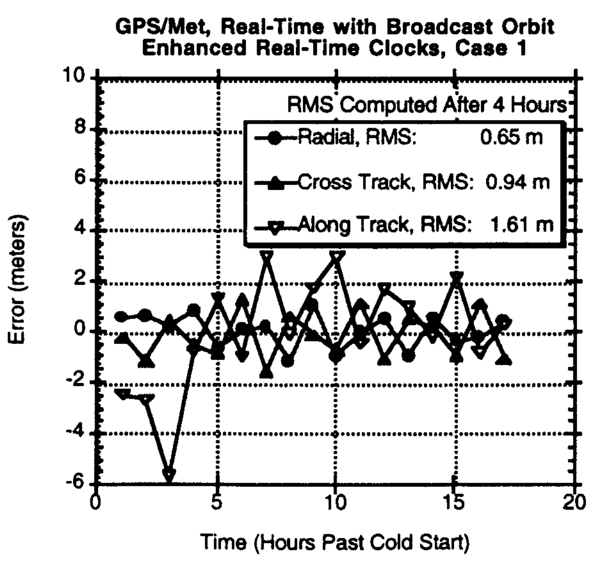

Fig. 7, Real-Time orbit using onboard data from GPS/Met on July 16,1996

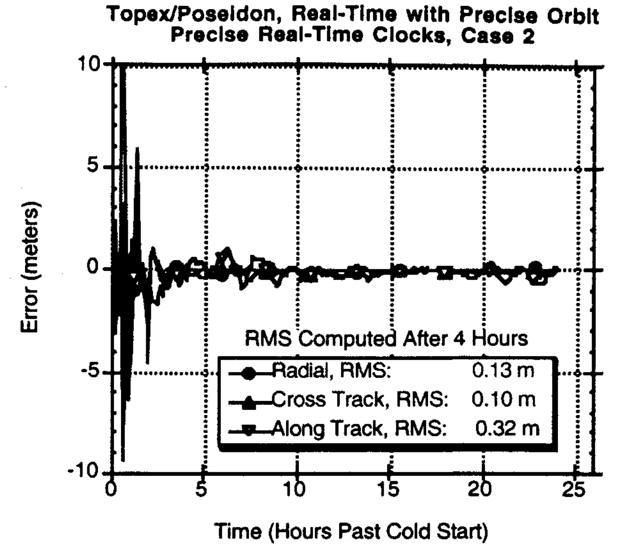

Fig. 8, Topex/Poseidon Real-Time Positioning with Precise Orbits and Clocks

dual-frequency codeless receiver with its antenna mounted to the side to support radio occultation science experiments [*Kursinski et al.*, 1996]. This makes for poorer GPS observing geometry.

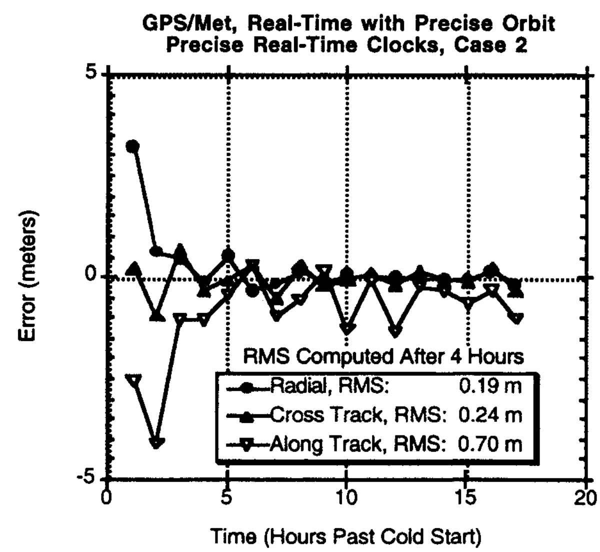

Fig. 9, GPS/Met at 700 km, Real-Time using precise orbits and clocks.

Precise Orbits and Clocks, Case 2)

Fig. 8 shows RMS accuracy at the decimeter level for radial and cross track components a few hours after an initial cold start. This is better performance than the 27 hour predictions to real-time shown in Table 2.

Fig. 9 shows the corresponding plot for GPS/Met with worse performance than Topex/Poseidon. The orbit for GPS/Met is lower and thus drag and gravitational forces are less well modeled. In addition to the poorer force modeling, the antenna on GPS/Met points off to the side, yielding poorer GPS observing geometry. The RMS accuracy was 20 to 70 cm compared to post-process truth orbits with better than 10 cm accuracy.

Conclusions

With improved onboard software, the current GPS system, using broadcast orbits and clocks can support low earth orbit real-time positioning at the 4-5 meter level. An example of such enabling software is RTG. RTG has been used in real-time for positioning of aircraft and will be used in sub-orbital tests of the X33.

Either global WADGPS or certain enhancements to the operational GPS system could support accuracy at the decimeter to meter level in the future. It is likely that a global WADGPS capability will be developed as multiple countries begin implementing compatible WAAS-type augmentations to GPS. U.S. government policy decisions could accelerate enhanced user positioning accuracy.

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